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Key Performance Indicators and Target Values for Multi-Megawatt Offshore Turbines

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Key Performance Indicators & Target Values for Multi-MW Offshore Turbines

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Introduction / Motivation

- This work is done in the context of Innwind.EU whose overall objective is the high performance innovative design of beyond state-of-the-art 10-20 MW deep offshore wind turbines.

- The assessment of innovation necessitates the establishment of a framework where different designs can be compared against a reference one on the basis of suitable key performance indicators (KPIs).

- These performance indicators are cost driven and evaluate the
  - Direct effect on Levelised Cost of Electricity (LCOE)
  - Indirect effect on downstream components (loads, weight)

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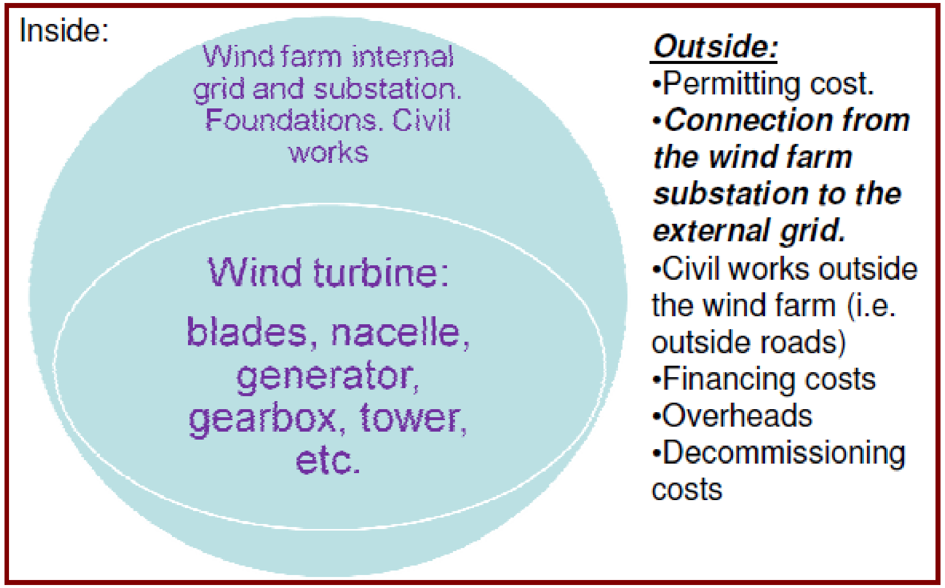
LCOE as a KPI for the European Industrial Initiative

The LCOE represents the sum of all costs over the lifetime of a given wind project, discounted to the present time and levelized based on annual energy production.

$$LCoE = \frac{(C+BOP) * FCR + O\&M}{AEP}$$

- *All turbine capital costs (C)*
- *Balance of plant incl the foundation, electrical cabling, logistics (BOP)*
- *FCR – fraction of capital costs per year*
- *Annualized O & M (OPEX)*
- *Annual energy production, AEP*



LCOE Targets for 2020 (EWII)

- The parameters needed for the LCOE calculation are:

PARAMETERS	ONSHORE	OFFSHORE
Capital investment cost – CAPEX (€/kW)	1 250	3 500
O&M costs including insurance(€/kW/yr)	47	106
Balancing costs (€/MWh)	3	3
Capacity factor (%)	25	40
Project lifetime (years)	20	25
Real discount rate (%)	5,39	5,39
Total plant capacity (MW)	40	300
Size of wind turbines (MW)	2.5	5-7

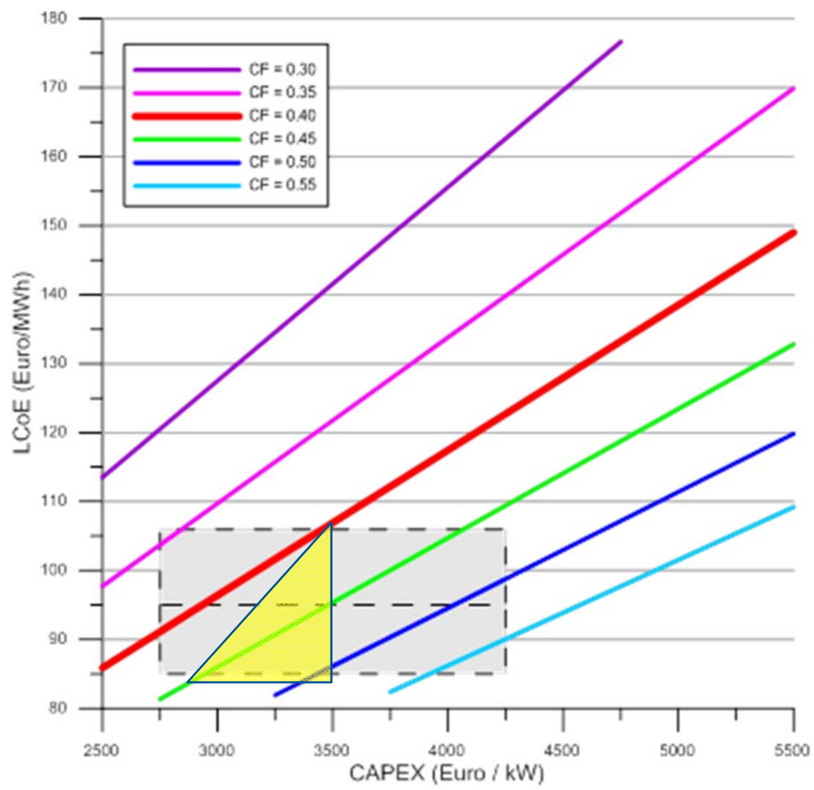
- The Table below shows the results of EWII-LCOE calculations assuming a linear reduction of the LCOE from 2010 to 2020 that reaches 20 % by 2020.

LCEO evolution	ONSHORE		OFFSHORE	
	Abs.	Rel.	Abs.	Rel.
LCOE by 2010 (€/MWh)	71,80	100	106,93	100
LCOE by 2015 (€/MWh) (-10%)	64,43	90	95,57	89
LCOE by 2020 (€/MWh) (-20%)	57,15	80	84,77	79

Support by:

LCOE Sensitivity to CAPEX and CF

- The Figure at right is quite instructive regarding the sensitivity of LCOE to its main drivers CAPEX and CF
- Calculations have been done with fixed OPEX = 106 (€/kW/yr)



NOTE: One percentage unit increase of CF has similar effect to LCOE as a 100 Euro/kW CAPEX reduction

Support by:

CAPEX Split for the Reference Case

		Roland Berger [5]		Ref [6]	Crown Estate- SITE B [7]	
		3MW Turbine	6MW Turbine	6MW Turbine	4 MW Turbine	8 MW Turbine
CAPEX SPLIT (M€ /MW)	*Turbine*	1,35	1,55	1,45 - 1,60	1,26	1,55
	Foundation	0,96			0,84	0,74
	Installation	0,62			0,71	0,36
	Electrics	0,58				
	Other	0,39			0,65	0,65
	SUM	3,51			3,46	3,30

Turbine	Rotor	*Rotor lock*		0,2357	1,00
		Blades	0,2220		
		Hub	0,0137		
	Nacelle systems	*Gearbox*	0,1291	0,2979	
		Generator	0,0703		
		Rotor brake	0,0132		
		Nacelle cover	0,0135		
		Nacelle structure	0,0280		
		Couplings			
		Shaft	0,0191		
		Yaw system	0,0125		
		Bearings	0,0122		
	Electrics & control	*Pitch system*	0,0266	0,0767	
		Variable speed sys	0,0501		
	Tower			0,2630	
	Other			0,1300	
BoP Only		*Foundation system*	0,4400		1,00
		Offshore transportation & installation	0,3000		
		Offshore electrical I&C	0,2600		

LCOE CALCULATOR		*ONSHORE WIND* EWII	*OFFSHORE WIND* EWII
Total Plant Capacity (MW)	P	40,00	300,00
Size of Wind Turbines (MW)	Pt	2,50	5,00
Turbines Cost (€/kW)	Ct	900	**1.500**
BoP Cost (€/kW)	Cb	350	**2.000**
Capital Investment Cost (€/kW)	C	1.250	3.500
O&M Costs (€/kW/y)	O&MF	47	106
O&M Costs [incl. fixed annual costs, (€/MWh)]	O&M	21,46	30,25
Balancing Costs (€/MWh)	BC	3,00	3,00
Project Lifetime (y)	N	20	25
Capacity Factor (%)	Cf	0,25	0,40
Nominal Discount Rate (%)	dn	0,07	0,07
Inflation Rate (%)	i	0,02	0,02
Real Discount Rate (%)	d	0,0539	0,0539
Capital Recovery Factor (%)	CRF	0,083	0,074
Summation of Discounted Future Expend	SFE	12,058	13,557
Present Value of Total O&M (€)	SO&M	25.838.573	473.853.240
Annual Energy Production (MWh/y)	E	87.600	1.051.200
Levelized Investment (€/y)	LI	4.146.514	77.452.842
AnnualLDiscounted O&M (€/y)	DO&M	2.142.800	34.953.600
Annual O&M / Capital Investment (%)	O&M(%)	0,038	0,030
	LI/E	47,33	73,68
	DO&M/E	24,46	33,25
LCOE (€/MWh)		**71,80**	**106,93**
Contribution of CAPEX (Turbines) (€/MWh)		34,08	31,58
Contribution of CAPEX (BoP) (€/MWh)		13,25	42,10
Contribution of OPEX (€/MWh)		24,46	33,25
Contribution of CAPEX (Turbines) (%)		0,47	0,30
Contribution of CAPEX (BoP) (%)		0,18	0,39
Contribution of OPEX (%)		0,34	0,31
		1,00	*1,00*

Split of Turbine & BoP CAPEX to its subcategories (5 MW HAWT)

LCOE Calculator

Support by:

Calculating LCOE for Up-scaled Designs

- To demonstrate the concepts we shall work with two up-scaling strategies, first with "classical up-scaling" and second with "innovation-based up-scaling", which implies the adoption of new technologies with a strong potential for cutting the costs (and weight) down but also for increasing the offshore wind farm capacity factor.

- The goal at this stage is not to identify these innovative technologies but to set targets on their desirable performance.

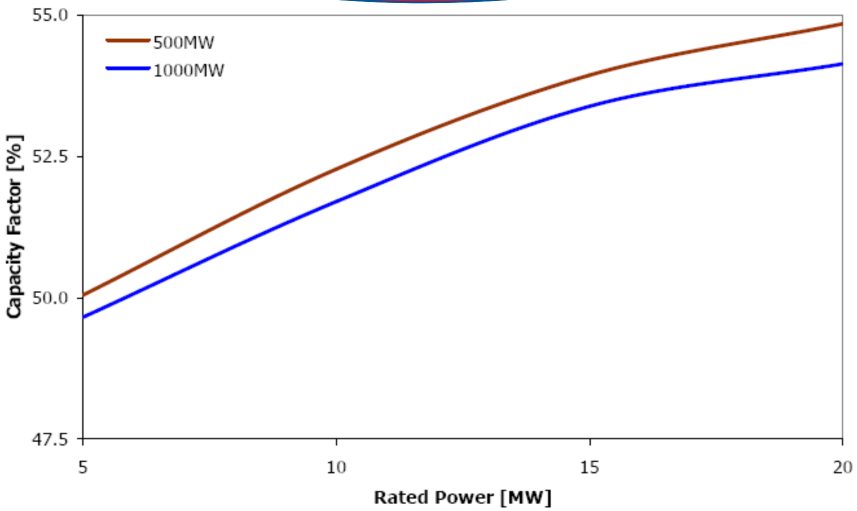
- We shall investigate up-scaling effects on Capacity Factor and Turbine and BoP CAPEX.

- OPEX investigations are not part of Innwind.EU. Increasing the turbine size reduces the OPEX per installed MW. Evidently, the OPEX part which is simply proportional to the number of turbines in the farm is getting down when larger turbines are used. We shall assume that a 10% reduction for the standard practices and a 20% reduction with innovative practices is feasible, following the turbine size increase from 5 to 10 MW.

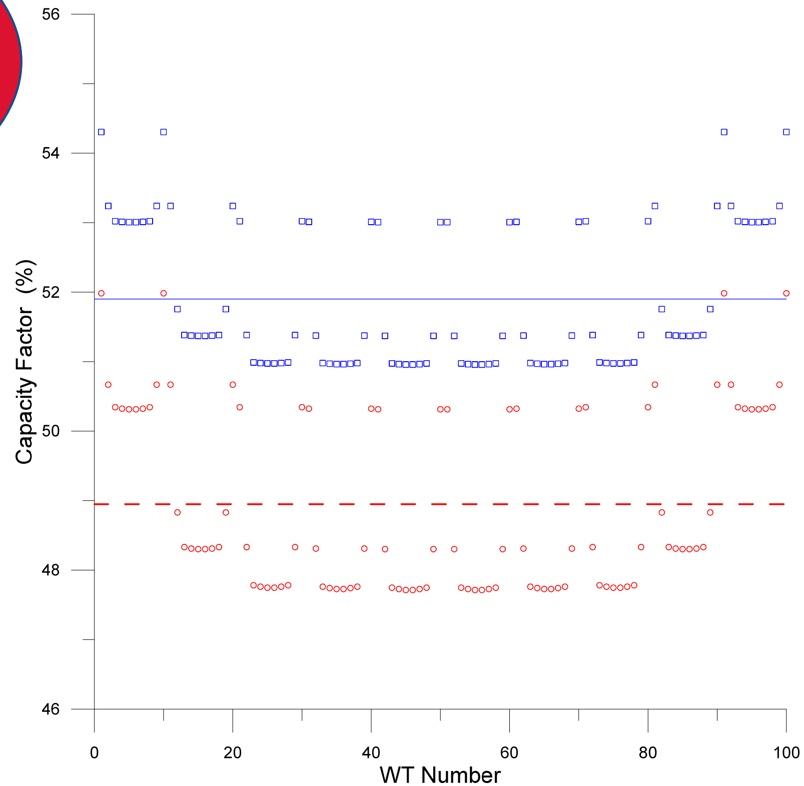
Support by:

Up-scaling and Wind Farm Capacity Factor

Add 3 percentage units for a standard design and 7 units for an innovative design when the turbine size is increased from 5 to 10 MW.



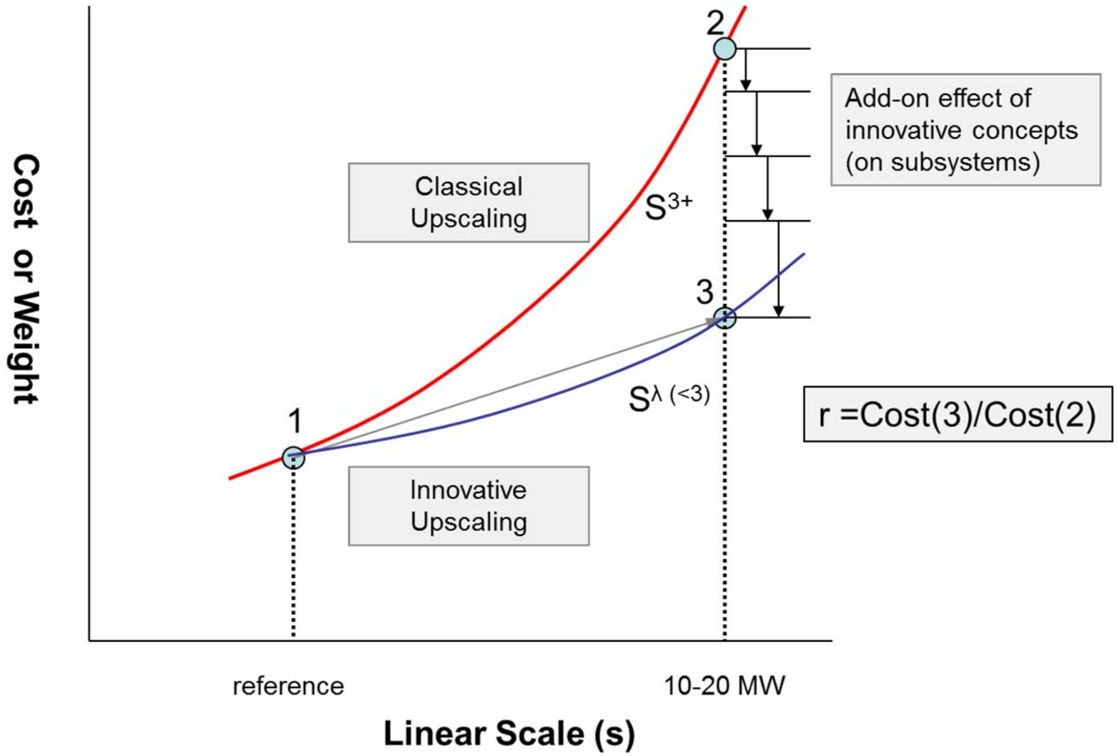
Classical Up-scaling
Effect of turbine size on the aerodynamic capacity factor of large offshore wind farms



Capacity factor and wake losses in a 10X10 offshore wind farm with 5 MW turbines at 8D spacing. Red dots refer to "standard" and blue squares to "low-induction" turbines.

Support by:

CAPEX - Scaling Exponent and Cost Reduction



$$(\lambda_{clas} - \lambda_c) ln[s] = -ln[r]$$

Up-scaling and CAPEX

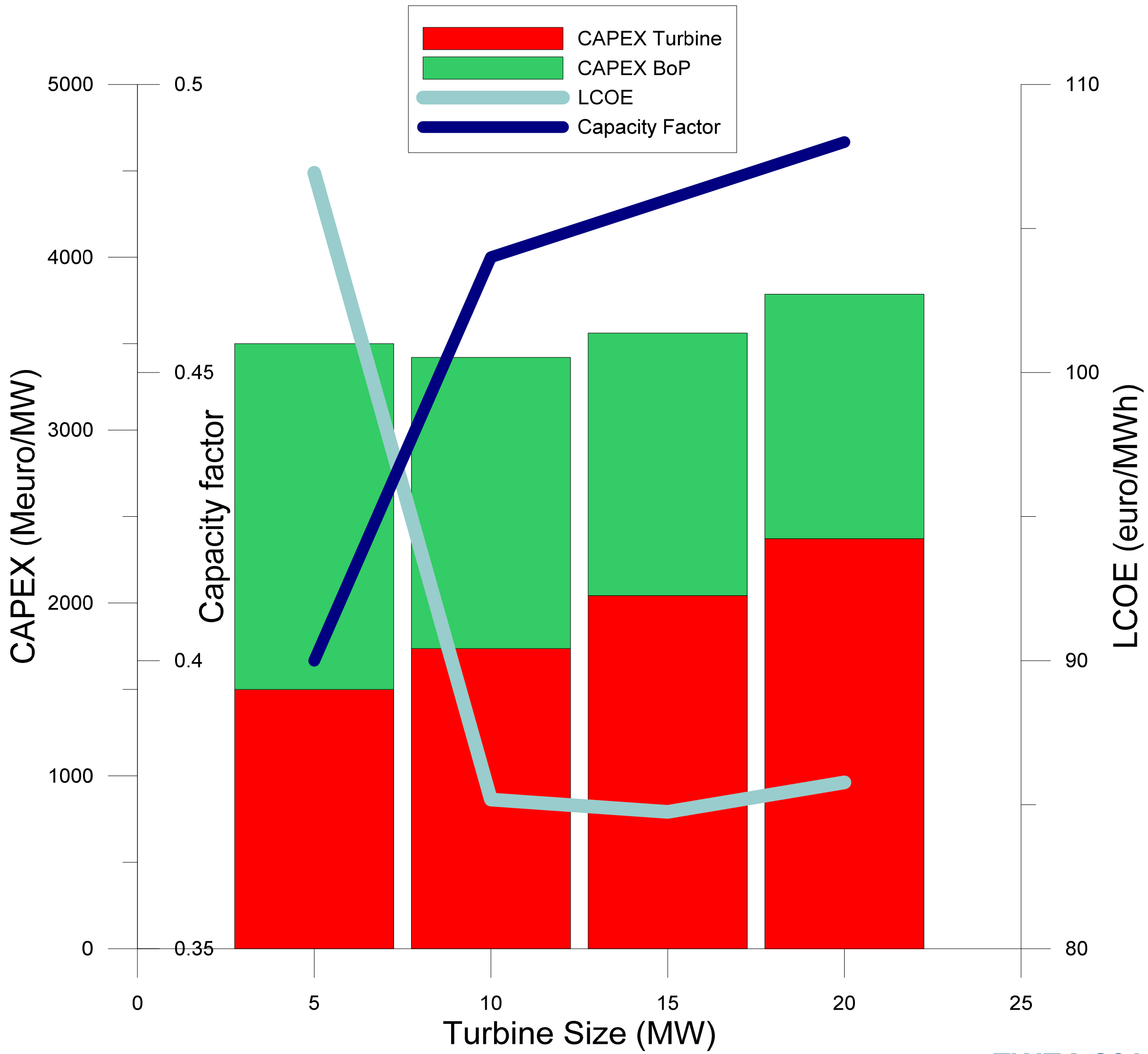
- In classical up-scaling we assume that the scaling exponent for CAPEX is λ_c=3 for the turbine and its main subcomponents and λ_c=2 for the BoP part. Namely, the Turbine CAPEX scales-up with s^3 where s is the linear scale factor.

- Our assumption for the BoP scaling exponent needs further discussion. UPWIND project showed that for a fixed water depth, the electrical infrastructure and connection scales-up with the power of the turbine (λ_c=2) and similar assumptions are made for the other BoP cost categories (offshore foundation system, transportation, installation etc. For a given water-depth and a bottom-mounted design it is logical to assume that the offshore foundation system (monopile, jacket) weight is scaling-up in two dimensions and not in three (as constrained by the fixed water-depth), thus λ_w=2.

- Going to our "innovation-based up-scaling" figures we shall assume λ_w values lower than 3 and 2 for the turbine and BoP parts respectively. For the turbine part every such λ drop is directly related to technological improvements while for the offshore substructure part the fact that the hub height in not up-scaling linearly but adjusts to a fixed blade-mean sea level clearance leads to λ_w values closer to 1.7 than 2.

Support by:

LCEO for Innovation-based Up scaling



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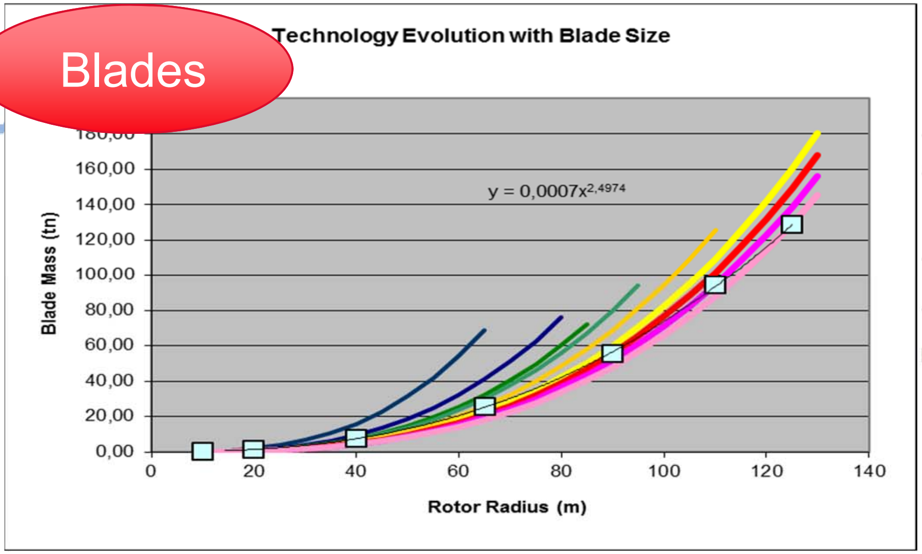
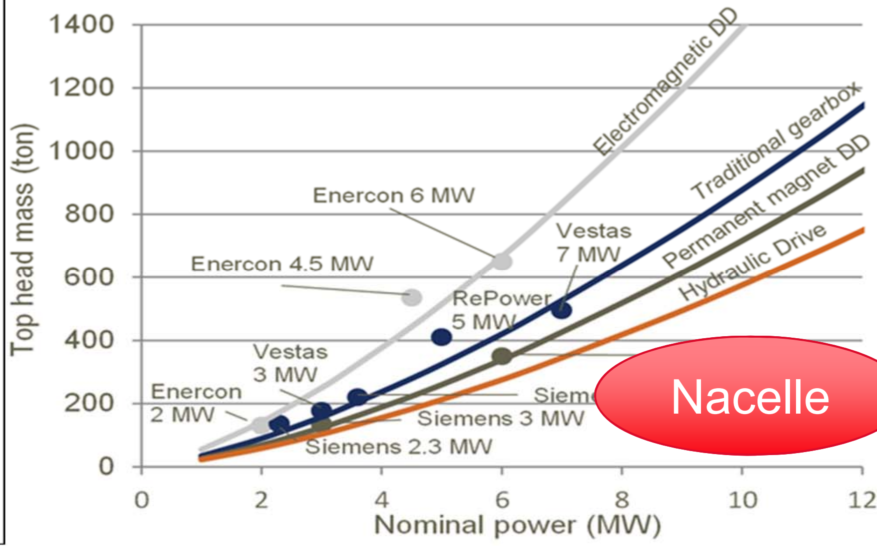
Support by:

Setting LCOE Targets at Sub-components Level

Blades





Nacelle

Tower optimization assuming a fixed blade–mean sea level clearance(h_{clear}), where the up-scaled tower is expressed as $H(s) = s.\frac{D_1}{2} + h_{clear}$ instead of $H(s) = s.H_1$) results in a scaling exponent $\lambda_w \cong 2{,}7$ instead of 3+

For the offshore foundation system assuming a given water-depth and a tubular structure the resulting scaling exponent of the optimized mass is $\lambda \cong 1{,}7$

Support Structure

Overall

	Innovative 10MW	
	s =	***1,41***
Subcomponent	**λ**	***r***
rotor blade	*2,30*	*0,78*
nacelle-system	*2,60*	*0,87*
tower	*2,50*	*0,84*
offshore fundation system	*1,50*	*0,59*

Support by:
SEVENTH FRAMEWORK PROGRAMME

Scaling Exponents and Cost Targets for 10 MW

REF TURBINE (EWEA 5 MW)								UPSCALED TURBINE						
Capacity (MW)	5,00						Turbine Upscaling Exponent 2,42	Capacity (MW)	10					
Turbine Cost (M€/MW)	1,500							Turbine Cost (M€/MW)	1,742					
						Subcomponent costs (M€)	Upscaling exponents							Subcomponent costs (M€)
Turbine Only	Rotor	*Rotor lock*	*0,0000*	**0,2357**	**1,00**	0,000	**2,50**	Turbine Only	Rotor	*Rotor lock*		**0,2276**	**1,00**	0,000
		Blades	***0,2220***			1,665	**2,30**			*Blades*	***0,2121***			3,695
		Hub	*0,0137*			0,103	**2,80**			*Hub*	***0,0156***			0,271
	Nacelle systems	*Gearbox*	***0,1291***	**0,2979**		0,968	**2,60**		Nacelle systems	*Gearbox*	***0,1368***	**0,3014**		2,384
		Generator	***0,0703***			0,527	**2,00**			*Generator*	***0,0605***			1,055
		Rotor brake	*0,0132*			0,099	**2,50**			*Rotor brake*	*0,0135*			0,235
		Nacelle cover	*0,0135*			0,101	**2,50**			*Nacelle cover*	*0,0138*			0,241
		Nacelle structure	*0,0280*			0,210	**2,50**			*Nacelle structure*	*0,0287*			0,499
		Couplings	*0,0000*			0,000	**2,50**			*Couplings*	*0,0000*			0,000
		Shaft	*0,0191*			0,143	**2,70**			*Shaft*	*0,0210*			0,365
		Yaw system	*0,0125*			0,094	**2,70**			*Yaw system*	*0,0137*			0,239
		Bearings	*0,0122*			0,092	**2,70**			*Bearings*	*0,0134*			0,233
	Electrics & control	*Pitch system*	*0,0266*	**0,0767**		0,200	**2,30**		Electrics & control	*Pitch system*	*0,0254*	**0,0685**		0,443
		Variable speed system	***0,0501***			0,376	**2,00**			*Variable speed system*	***0,0431***			0,752
	Tower		***0,2630***	**0,2630**		1,973	**2,50**		Tower		***0,2693***	**0,2693**		4,691
	Other		*0,1300*	**0,1300**		0,975	**2,50**		Other		*0,1331*	**0,1331**		2,319
						7,525								**17,422**
							BoP Upscaling Exponent 1,50							
BoP Cost (M€/MW)	2,000					Subcategory costs (M€)	Upscaling exponents	BoP Cost (M€/MW)	1,684					Subcategory costs (M€)
BoP Only		*Foundation system*	***0,4400***		**1,00**	4,400	**1,50**	BoP Only		*Foundation system*	***0,4394***		**1,00**	7,400
		Offshore transportation and installation	***0,3000***			3,000	**1,00**			*Offshore transportation and installation*	***0,2519***			4,243
		Offshore electrical I&C	***0,2600***			2,600	**2,00**			*Offshore electrical I&C*	***0,3087***			5,200
						10,000								**16,843**

Downstream Influence

			Rotor Mass		Nacelle Mass		Tower Mass		OF Mass	
	λ_from	λ_to	λ_from	λ_to	λ_from	λ_to	λ_from	λ_to	λ_from	λ_to
Rotational Speed	-1,00	-0,80	?	?	3,00	2,80				
Tower-Top Mass	3,00	2,30					2,70	2,65	1,70	1,66
Max Design Thrust	2,00	1,60	?	?	?	?	2,70	2,46	1,70	1,53

- For bottom-mounted designs a drastic reduction of the nacelle mass does not have an equally important effect on tower and foundation masses. Thus, for bottom-mounted offshore designs, the reduction of the tower-head mass if not followed by an associated cost reduction (rotor or drive train) or an increase of the turbine capacity factor is not a target by itself and it can by no means pursued at the cost of drive train efficiency.

- This statement is not valid for floating designs where the tower-head mass might be an important driver of the cost of the floater.

- Contrary to tower-head mass, the sensitivity of the overall support structure mass to the maximum (design) thrust is significant.

Support by:

Conclusions

- A 20% LCOE drop from present values until 2020 seems quite feasible for deep offshore wind farms. Large (10 MW+), offshore-dedicated, wind turbines designs will be needed for that.
- For fixed water depth, the optimum sizing of the turbine derives by balancing the extra turbine cost with the lower BoP cost per MW as the turbine size increases. This is a common conclusion in all offshore cost studies. It looks that as the water depth increases larger turbines will be the optimum bottom-fixed solution. Nevertheless, this optimum size is still very much dependent on how successful we'll be in implementing new lower cost technologies in turbine and offshore substructure designs.
- Significant LCOE reduction can be expected by improving the wind farm capacity factor. This can be done by using larger turbines with low induction (low-thrust) rotors for better aerodynamic performance and by improving the efficiency of the drive train, power electronics and array cables.
- For bottom-mounted offshore designs, the reduction of the tower-head mass if not followed by an associated cost reduction or an increase of the turbine capacity factor is not a target by itself. This statement is not valid for floating designs where the tower-head mass might be an important driver of the cost of the floater.
- Contrary to tower-head mass, the sensitivity of the overall support structure mass to the maximum (design) thrust is significant.

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